

Introduction To SAR

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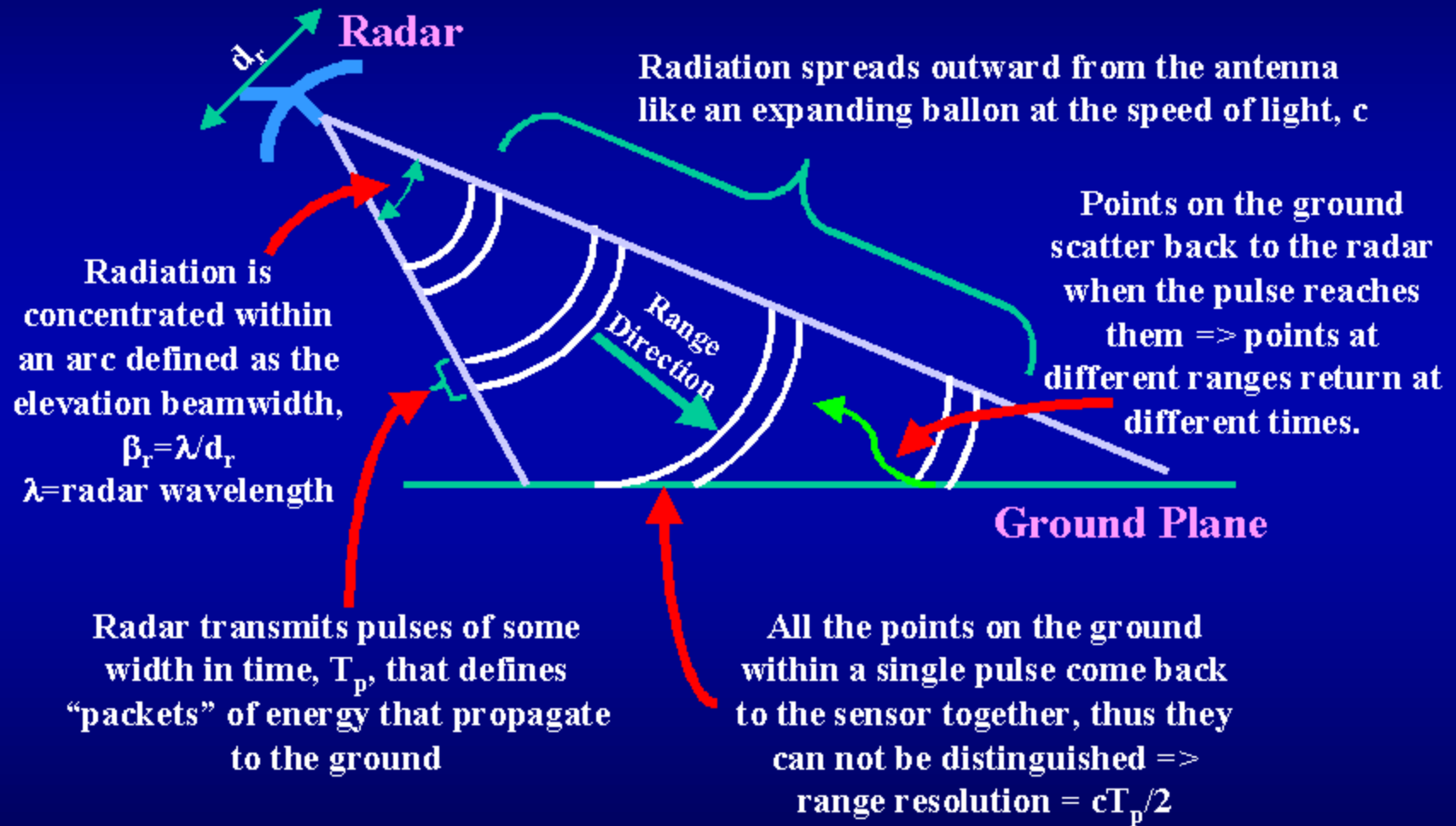
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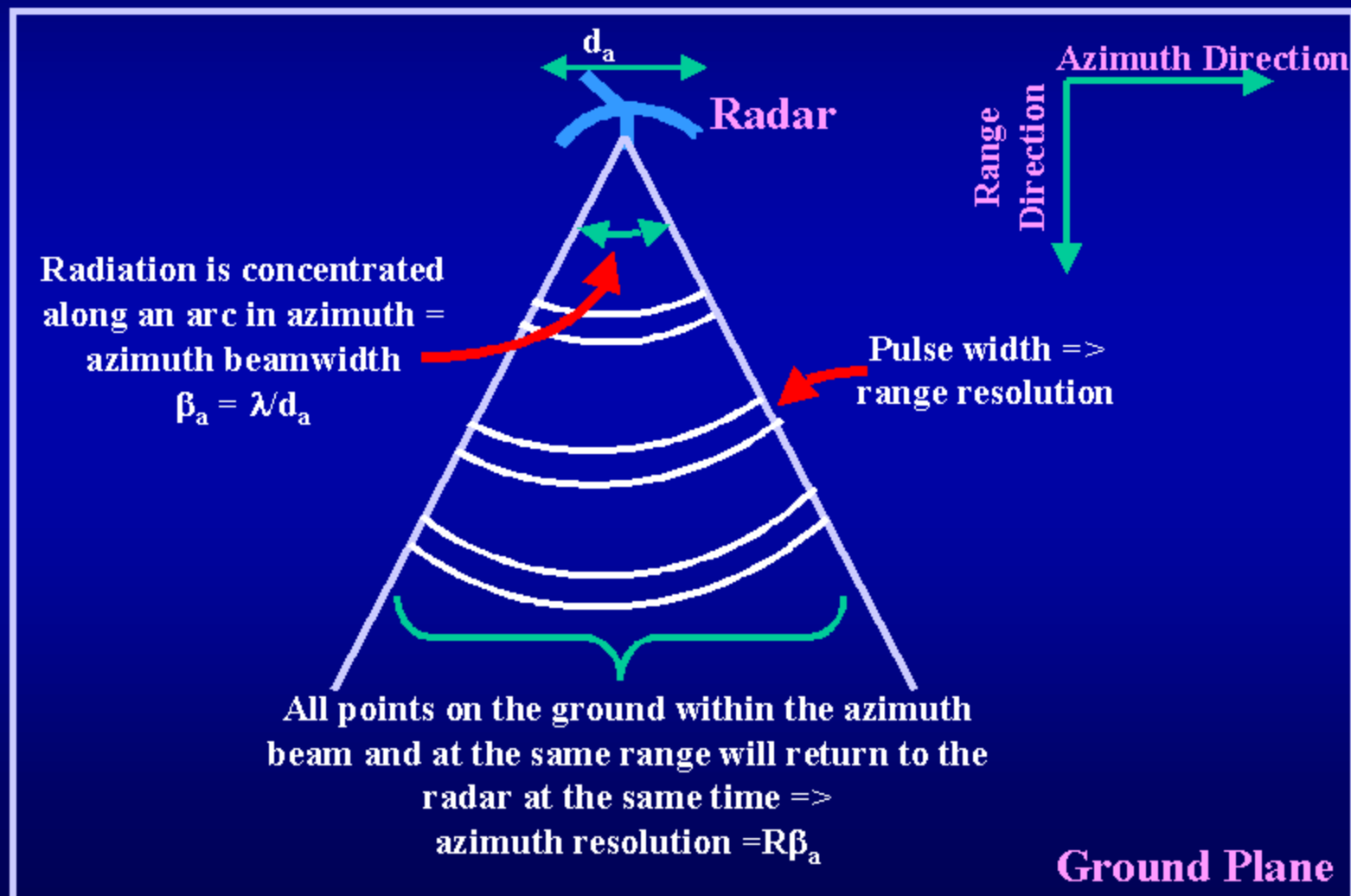
Introduction To Synthetic Aperture Radar (SAR)

- **How does a radar work.**
- **SAR versus real-aperture-radar**
- **SAR image formation**
- **SAR ocean imaging**
- **SAR land/ice imaging**
- **SAR applications**

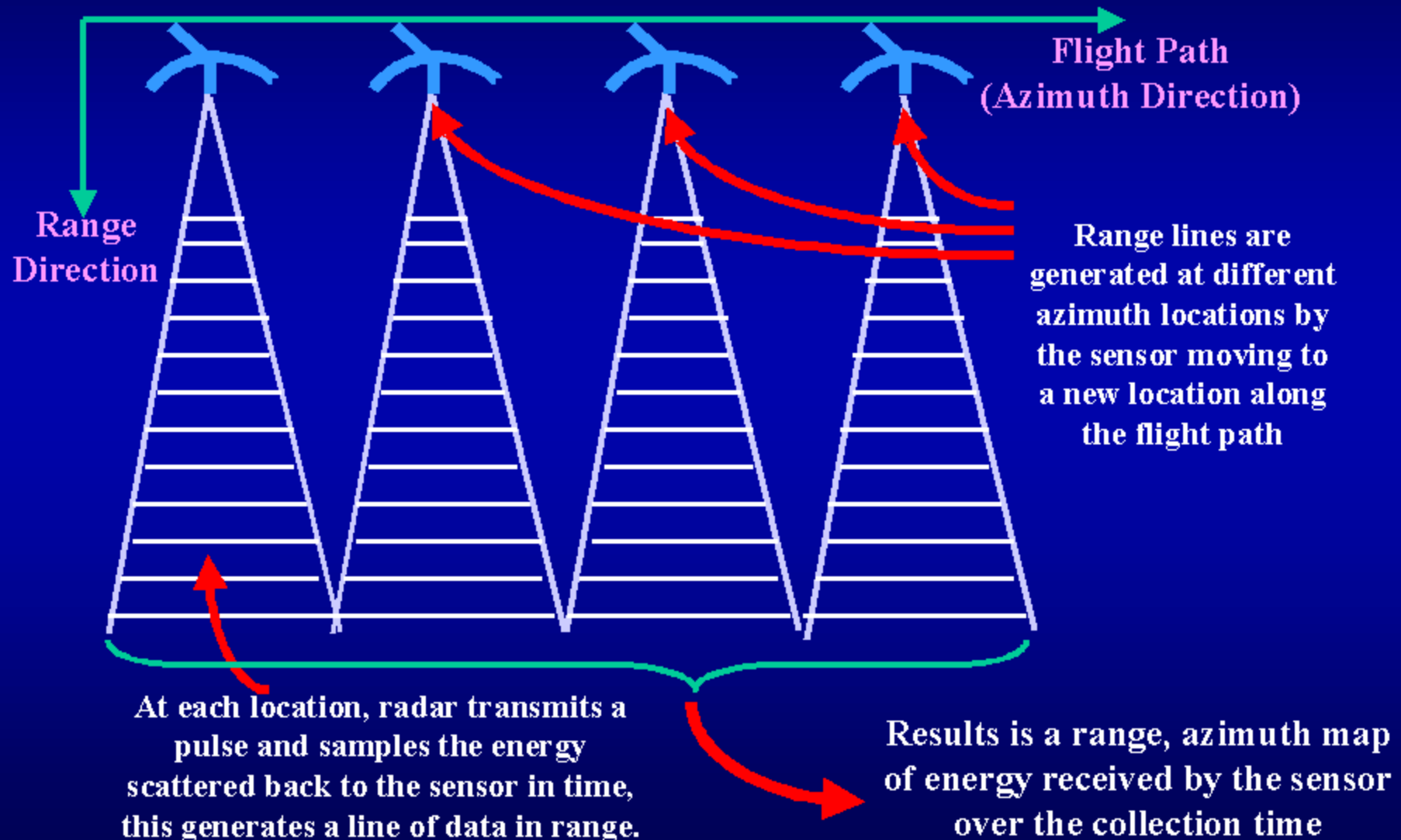
Radars Are Active Sensors That Transmit Microwave Radiation in Pulses Then Record Backscattered Energy



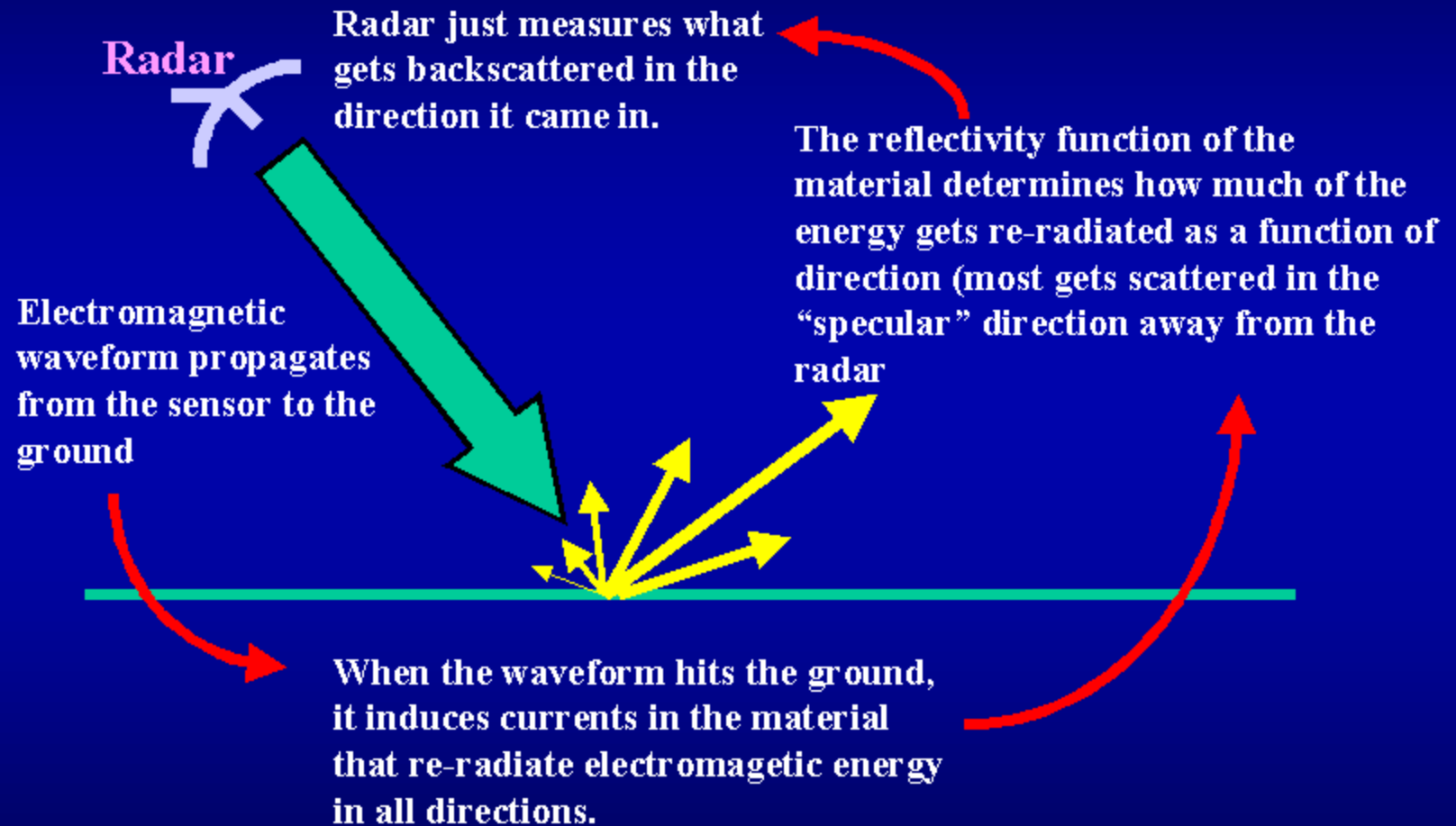
Radars Are Active Sensors That Transmit Microwave Radiation in Pulses Then Record Backscattered Energy



How a Radar Forms An Image



What a Radar Measures



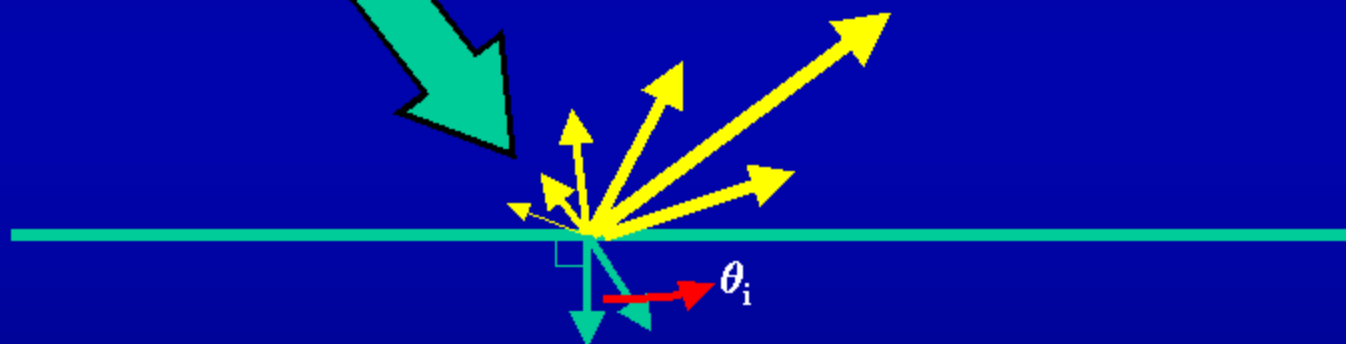
Radar Cross Section

What gets scattered back to the radar by a given material is defined as its *radar cross section*



$$\sigma = \frac{(\text{power backscattered per unit solid angle})}{(\text{incident power density} / 4\pi)}$$

Units of σ are meters^2 or dB-meters^2

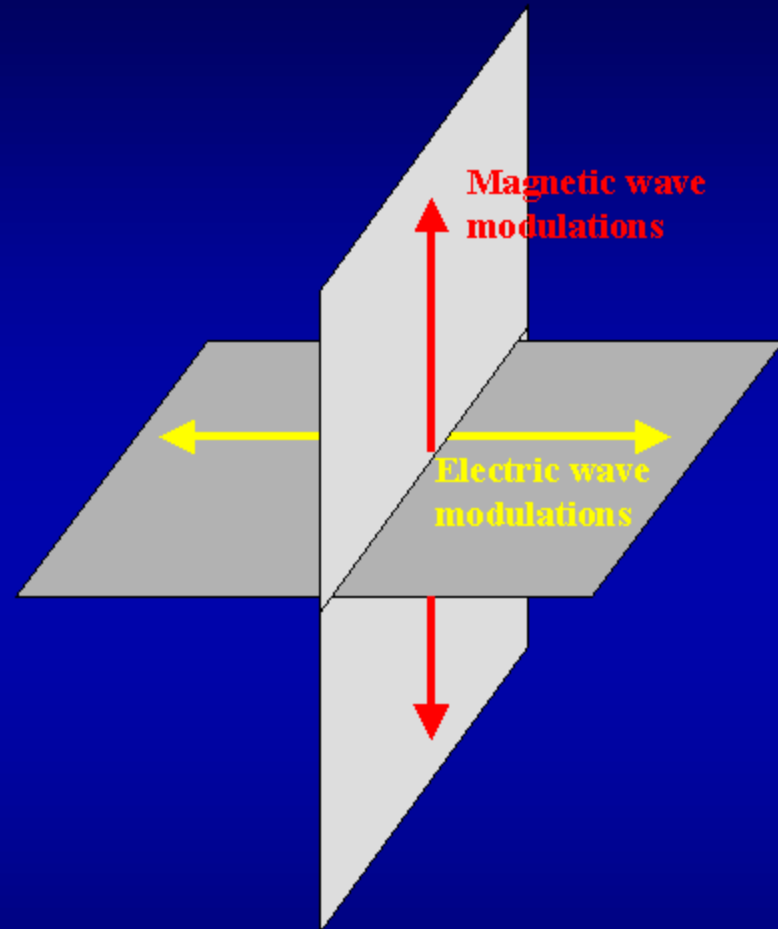


- σ depends on:
- (1) the roughness of the material (rougher => higher)
 - (2) the dielectric constant of the material (wetter => higher)
 - (3) local incidence angle θ_i (smaller => high)
 - (4) radar wavelength, polarization

For a clutter target (grass, trees, water, etc.) define a normalized radar cross section, σ_o , as σ per unit area of the clutter ($\text{meters}^2/\text{meters}^2$)

Radar Polarization

- Electromagnetic waves consist of orthogonal electric and magnetic waves changing in time
- The orientation of the plane in which the electric wave is moving determines the *polarization* of the radar
 - *horizontal polarization* => the plane is oriented right-left
 - *vertical polarization* => the plane is oriented up-down
- Can also have circular polarizations



Example Radar Cross Section Values

Sparrow = 0.001 m² or -30 dB-m²

Man = 0.7 m² or -1.5 dB-m²

F-4 = 4 m² or 6 dB-m²

Jeeps, cars = 100 m² or 20 dB-m²

Small cruiser = 4.3 x 10⁴ m² or 46 dB-m²

(from F.E. Nathanson, Radar Design Principles, 2nd ed., 1991)

Sphere = πr^2

Cylinder = $2\pi r L^2/\lambda$

Flat Plat = $4\pi A^2/\lambda^2$

Corner Reflector = $4\pi e^4/3\lambda^2$

Wet soil ~ 1 m²/m² or 0 dB

Vegetation ~ .15 m²/m² or -8 dB

Dry soil ~ .1 m²/m² or -10 dB

Water ~ .01 m²/m² or -20 dB

Advantages of Microwave Radars

- **Since they are active sensors (providing their own illumination) they can operate at night**
- **Microwave radiation passes through clouds and rain essentially unaffected, so images can be made in all weather**
- **Radars are relatively easy to build and can be put on the ground, in airplanes, and on satellites**
- **Radars only record the energy of the scattered field (easier electronic to build)**

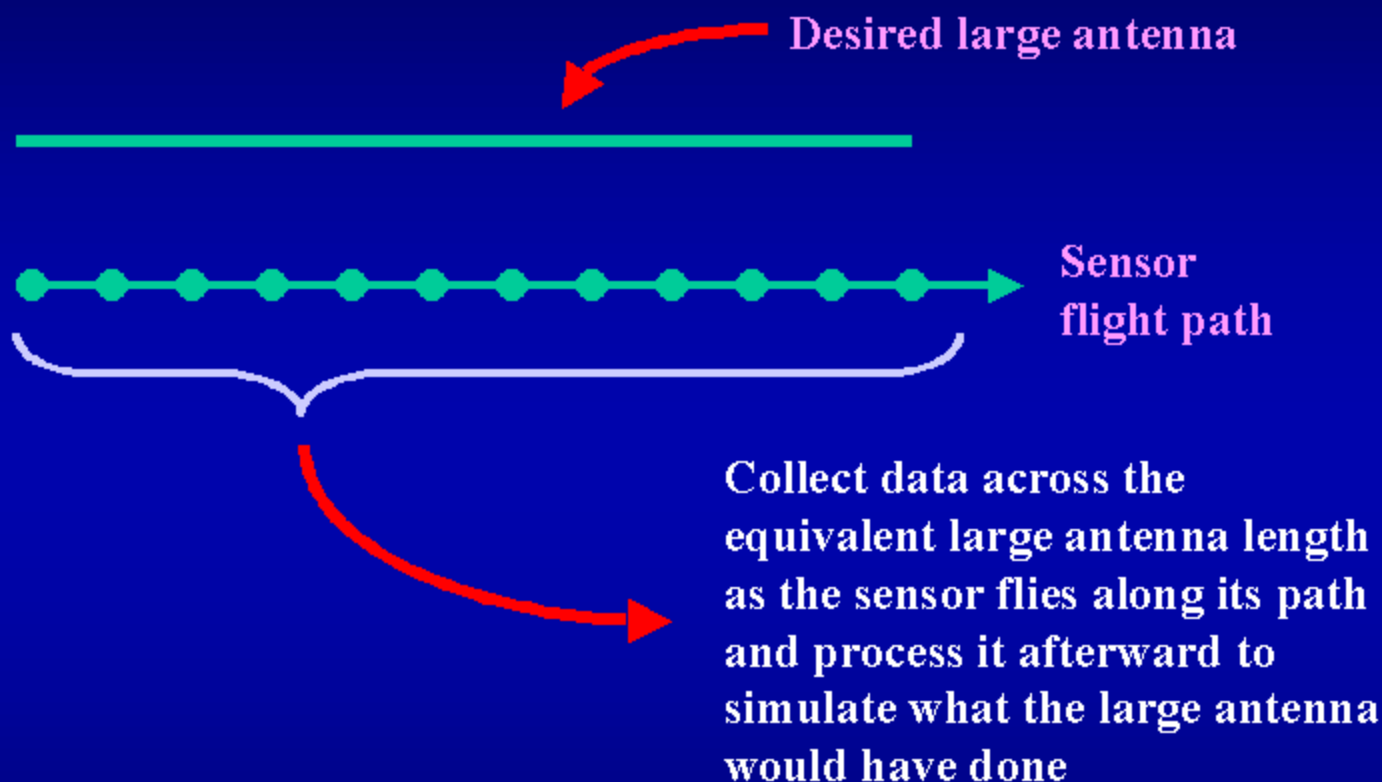
Disadvantages of Microwave Radars

- Range resolution is limited by pulse width
 - very small resolution requires very short pulse
 - if the radar is in an airplane or satellite, the pulse must contain a lot of energy to survive the trip to the ground and back
 - could not build equipment to force that amount of energy through the system in such a short time
- This was solved by “encoding” the pulse into an extended waveform to increase the time required to force the energy through the system
 - implied that you had to “decode” the pulse before you could see an image

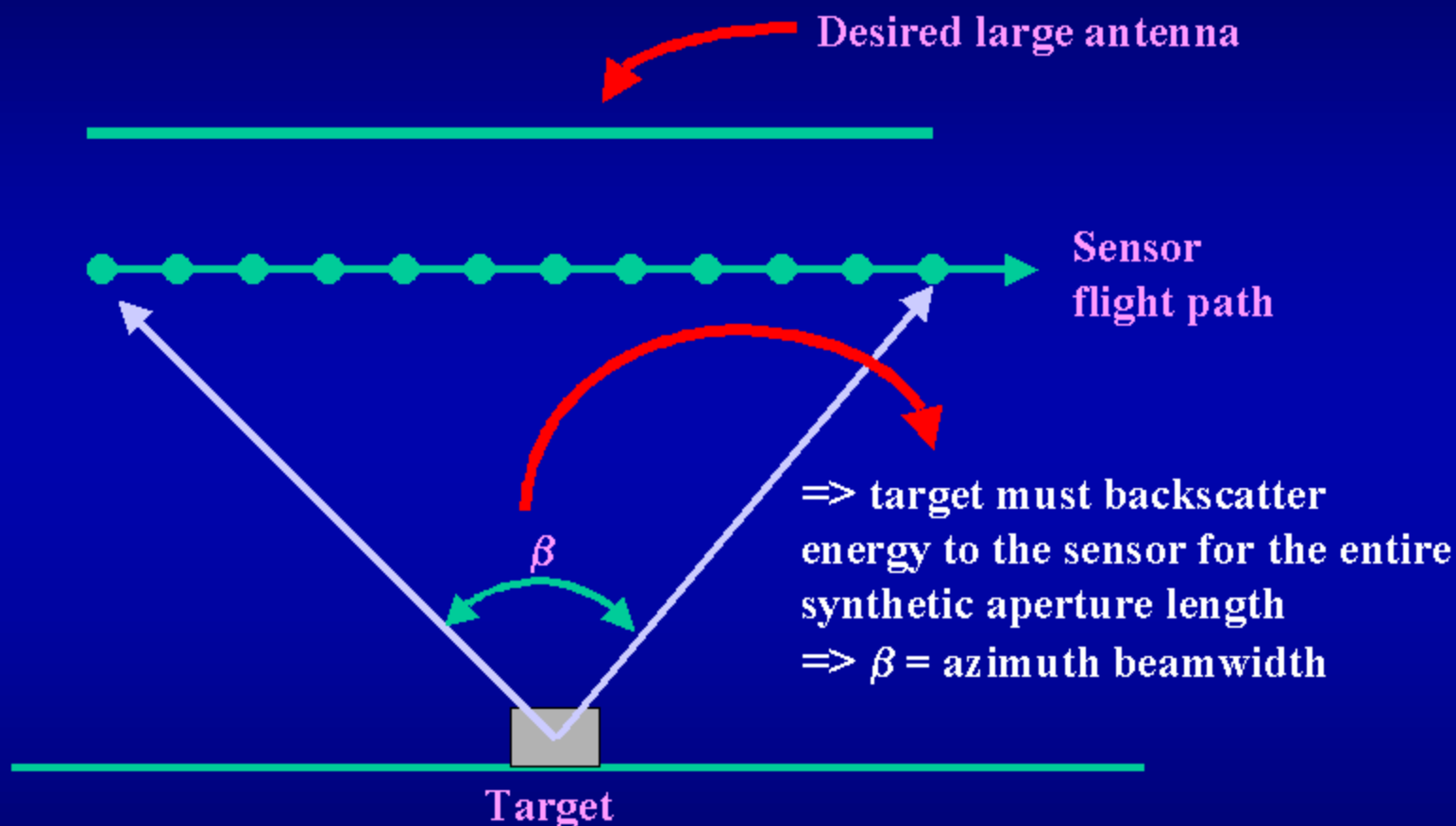
Disadvantages of Microwave Radars (cont.)

- Azimuth resolution was determined by the azimuth beam pattern
 - resolution increased with range
 - smaller resolution meant larger antennas ($\beta_a = \lambda/d_a$)
 - antennas became too large to realistically mount on an airplane
- This was solved by using a small antenna to “synthesize” what a larger antenna would have collected, thus generating a synthetic antenna or aperture

Synthesizing An Antenna Aperture



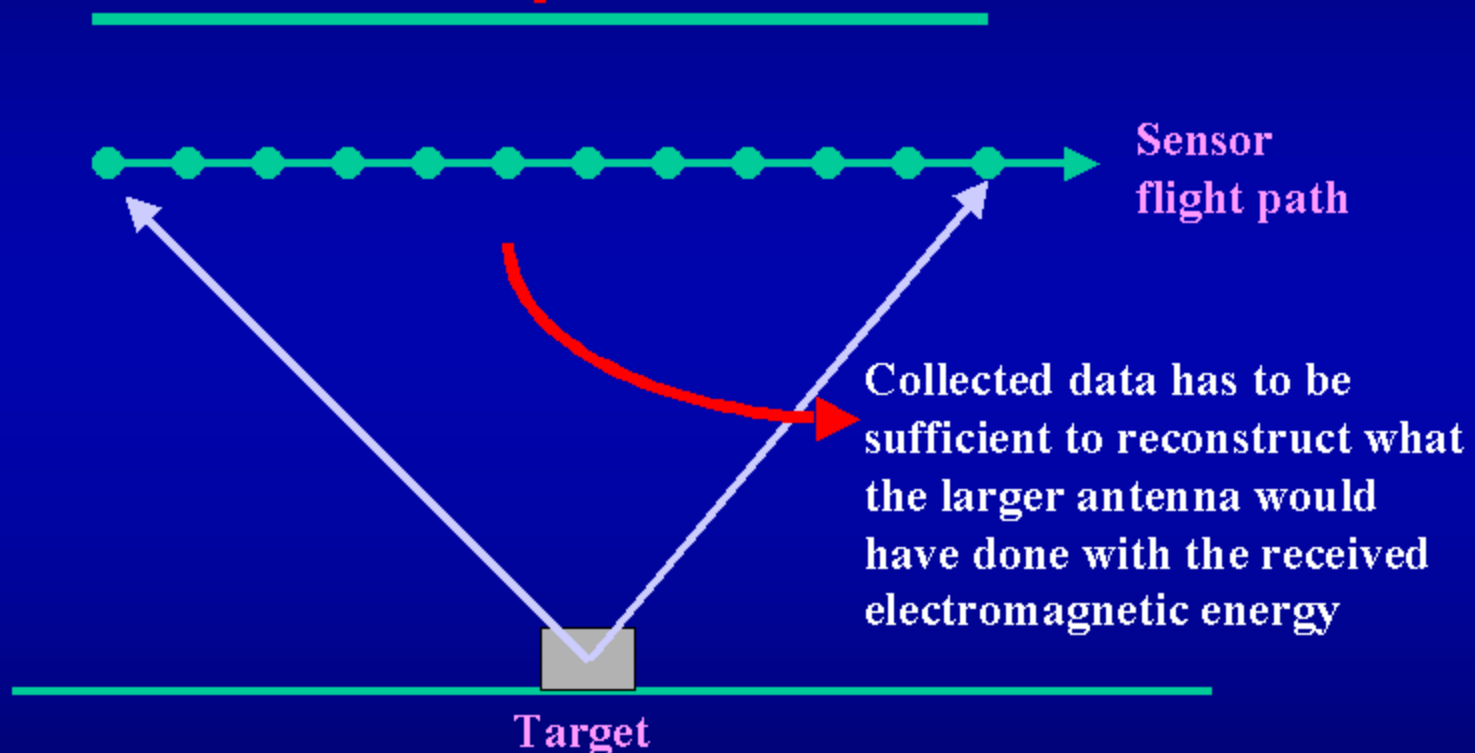
Synthesizing An Antenna Aperture (cont.)



\Rightarrow larger azimuth beamwidth (smaller antenna) generates better resolution (!!!) since it generates a larger synthetic aperture

Synthesizing An Antenna Aperture (cont.)

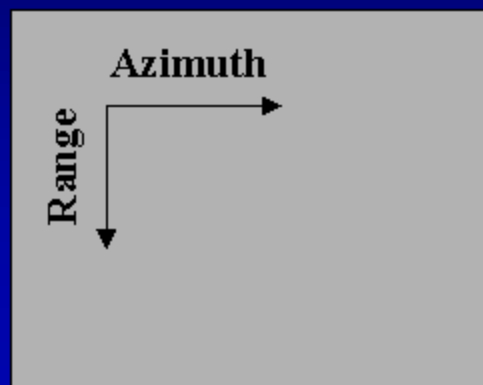
An antenna corrects the waveform impinging across its entire surface for the differences in travel time, then sums the corrected energy along its length



Sensor needs to record both the magnitude and the phase of the received energy in order to correct the phase of the energy along the flight path before summing the received energy for each target

Synthesizing An Antenna Aperture (cont.)

Data collected by a SAR



SAR Image



Model for the change in phase of a point target as the SAR flies by
 $= \exp[i4\pi R/\lambda]$



Correlation

Modeling what a large antenna would have done is performed by correlating the data by a model of the phase changes from a point target. When the model is over the target response, it will correct the phases and sum up the energy

SAR Image Formation

- The process of “synthesizing” the larger antenna by correlating the data with a point target model is the image formation process
- It is essentially “decoding” the responses in azimuth back into a point
- The change in phase of the received data as the SAR moves past the target is caused by a doppler shifting of the radiation
 - SAR is often called a doppler radar

SAR Image Formation (cont.)

- This image formation process is computationally intense
 - two-dimensional correlations are required on large data sets
- The azimuth model used in the correlation ($\exp[4\pi R(t)/\lambda]$) is determined by the change in range between the SAR and the target, $R(t)$
 - errors in flight or ephemeris information cause significant image smearing
 - unknown motions of the target cause significant smearing and shifting

SAR Advantages / Disadvantages

- Advantage is much finer azimuth resolution
 - can show that resolution = $d_a/2$
 - can show that resolution is independent of range
- A number of disadvantage come along
 - requires measuring both magnitude and phase of the received signal (harder to build)
 - requires knowing the flight path to within the radar wavelength (motion compensation equipment is require)
 - very sensitive to target motions
 - requires complicated post-processing to generate an image

SAR Target Motion Effects

- If there is a velocity component in the range direction, v_r , from the target, it will be shifted in the image in the azimuth direction by $(R/V)v_r$ where R = range to target, V = sensor velocity
- If there is a change in v_r over the collection time, Δv_r , then the target will be smeared in azimuth with a half-width of $(R/V)\Delta v_r$
- If there is an azimuth velocity component, v_a , it will smear the target in the azimuth direction by $(R/V)v_a$

Bragg Scattering

When the radar wavelength, λ ,
projected onto the surface
matches a periodic structure on
the surface, there is a resonance
effect causing a strong backscatter
 \Rightarrow *bragg scattering*

$$\sigma_o = 8\pi \cos^4(\theta_i) S(2k \sin(\theta_i'), \Phi) |R|^2$$

θ_i = radar incidence angle

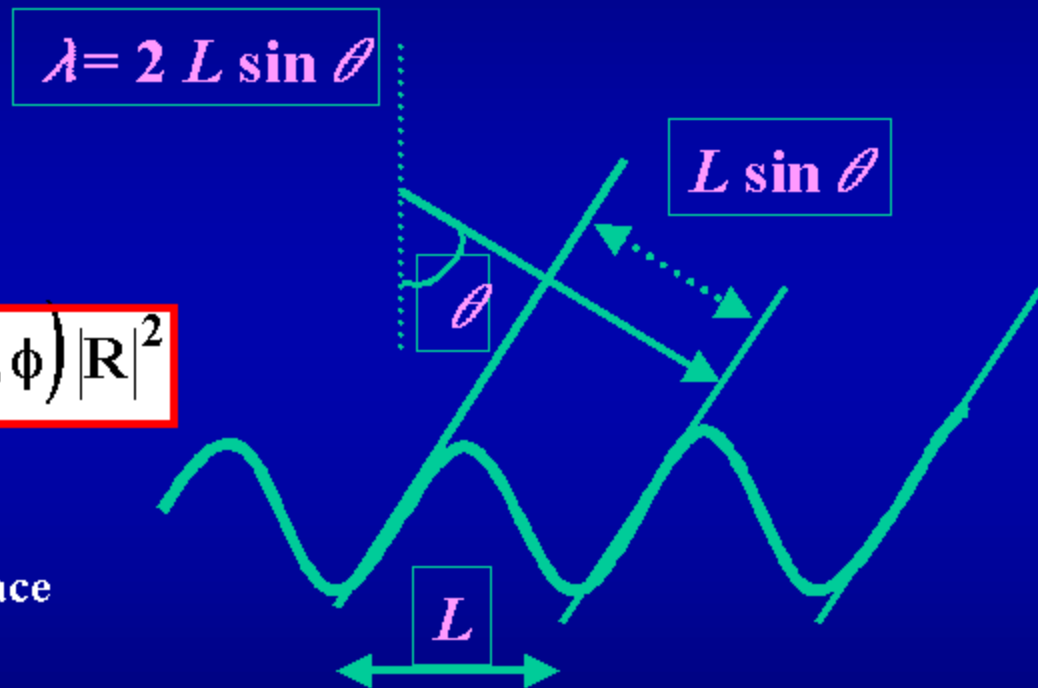
θ_i' = local incidence angle of surface

$S(k, \Phi)$ = spectrum of surface

k = radar wavenumber = $2\pi/\lambda$

Φ = look direction of the radar

R = reflectivity constant (depends on dielectric constant, θ_i)



(copied from Frank Monaldo, APL)

Bragg Scattering (cont.)

- σ_0 is proportional to the amplitude of the “bragg wave” (the wave on the surface that matches the bragg condition) only
 - this is the only surface structure the radar “sees”
- Radar only “sees” the bragg waves that are moving toward or away from the sensor (moving in the Φ direction)
- A local tilting of the surface changes the local incidence angle θ_I and thus changes the wave on the surface that matches the bragg condition

SAR Ocean Imaging

- For SAR incidence angles between 20 and 60 degrees, *bragg scattering* is the dominant backscatter mechanism
 - for angles less than 20 degrees, specular scattering becomes dominant

$$\sigma_o = \frac{\pi}{\cos^4(\theta_i)} |R_o|^2 \exp[-4k^2 \sigma_h^2] p$$

R_o = reflectivity for specular surface

σ_h^2 = small-scale height variance

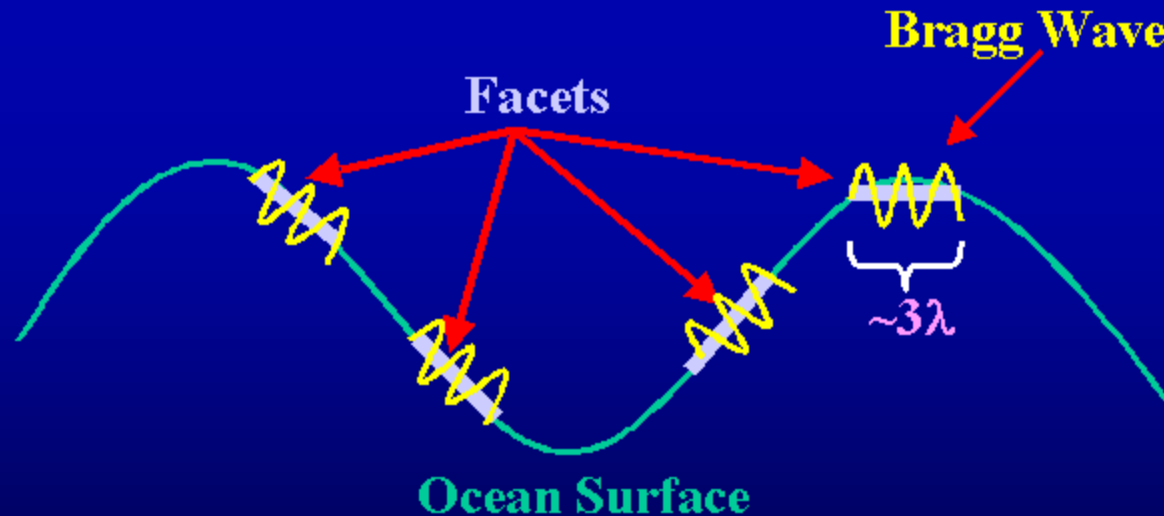
p = probability of a specular surface, $\theta_i' = \tan(\theta_i)$

- for angles greater than 60 degrees, no standard theory applies, but surface shape seems to become important

SAR Ocean Imaging (cont.)

Two-Scale Model

Model the ocean surface as a set of flat facets. Each facet is $\sim 3\lambda$ in length. The radar cross section from each facet is determined by bragg scattering \Rightarrow determined by the amplitude of the bragg waves within the facet and the local tilt of the facet caused by large-scale waves



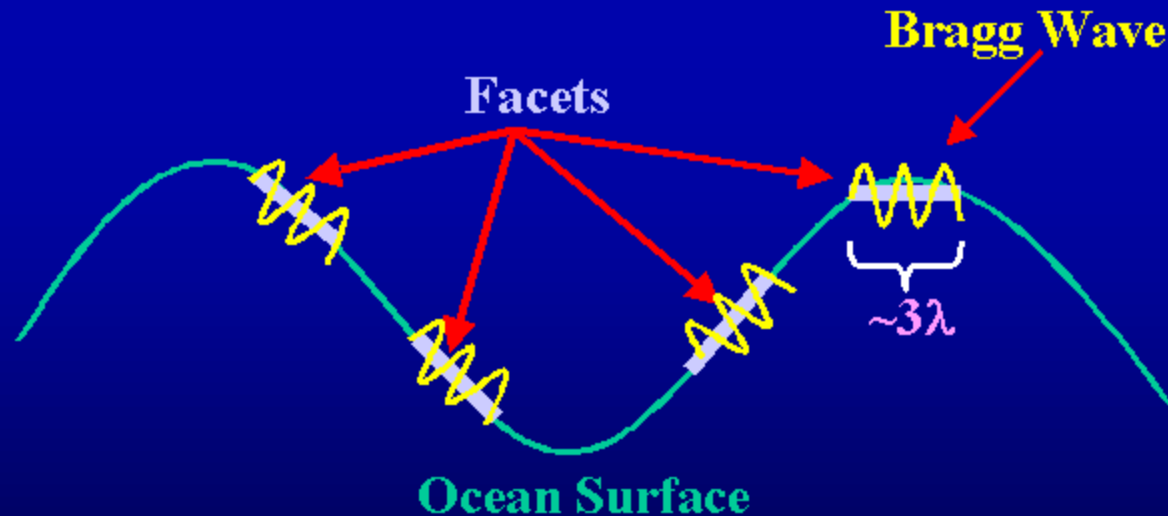
SAR Ocean Imaging (cont.)

Bragg waves are created by the local wind then propagate along the surface

=> amplitudes are determined by local wind conditions and ocean surface currents they encounter

Facet tilts are caused by the amplitudes of the long-scale waves

=> determined by local winds, swell

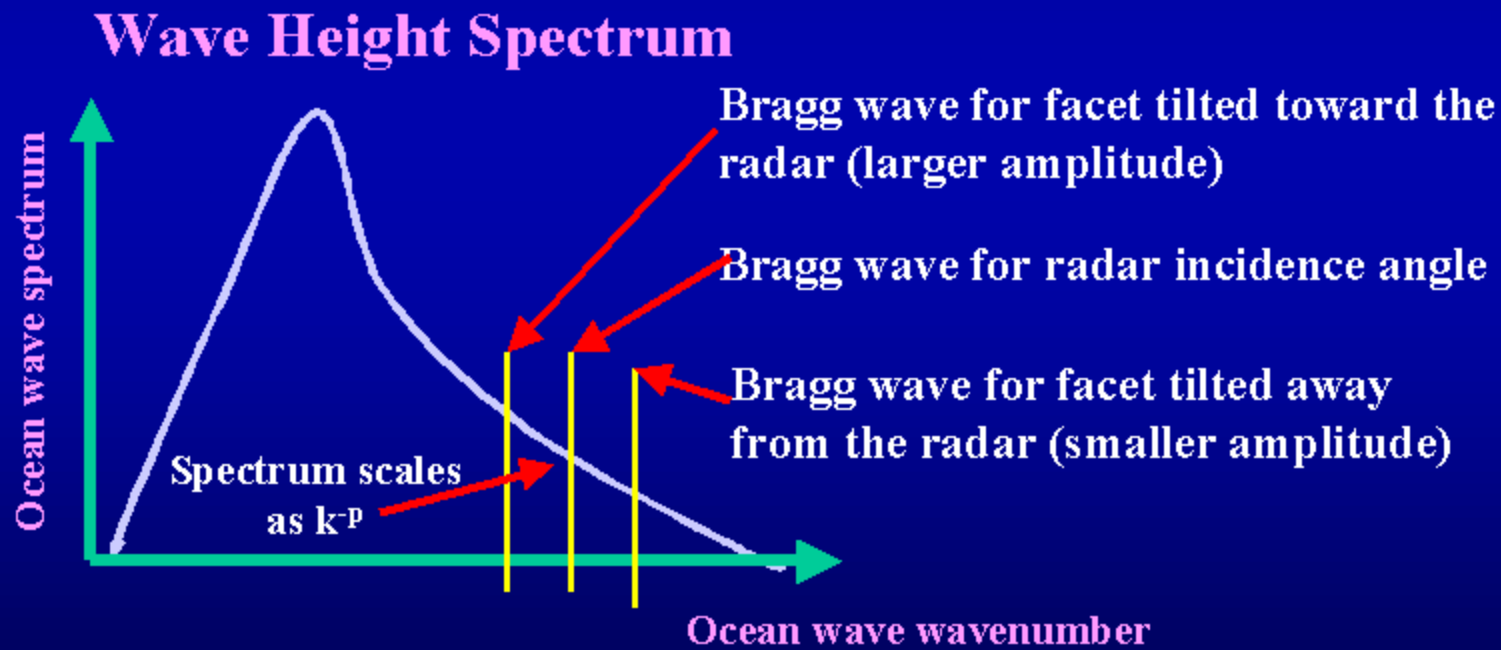


SAR Ocean Imaging (cont.)

- SAR imaging of large-scale ocean structures (waves, fronts, surfactants, etc.) is always an indirect effect
 - SAR only sees the effect that the large-scale structures have on the bragg waves
- Ocean surface is always moving which causes image smearing
 - azimuth resolution of a SAR image of the ocean is $(R/V)\sigma_v$ where σ_v is the standard deviation of bragg scatterer velocities within a facet ($\sigma_v \sim 0.2$ to 0.4 , R/V for an airplane $\sim 50 - 80$, R/V for a satellite $\sim 110 - 150$)

SAR Ocean Imaging (cont.)

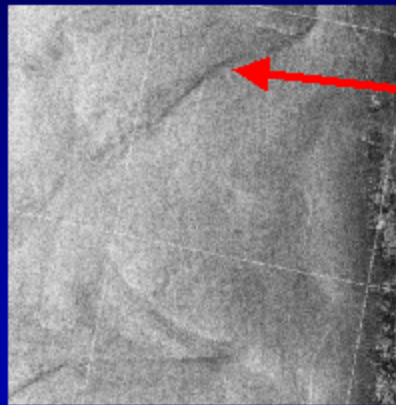
Tilting the facet changes the amplitude of the bragg wave because the wave height spectrum is not flat around the bragg wave location => knowing the spectrum in this bragg region is very important to SAR ocean imaging (models range from k^{-4} to k^{-8})



How Does A SAR Image ...

- **large-scale waves**
 - orbital velocities induce currents on the surface that affect the bragg wave amplitudes, local surface slope tilts the local facets
- **current fronts**
 - bragg wave amplitudes are affected as they cross the current front, bragg waves are refracted
- **oil spills, surfactents**
 - dampens the ocean surface, removing all bragg waves => no backscatter
- **local wind**
 - wind speed/direction changes bragg wave amplitude
- **internal waves**
 - wave propagation caused modulation of surface currents, the bragg waves pass through these currents and change their amplitudes
- **bathymetry**
 - flow over the bathymetric feature (usually tidal flow) causes modulation of surface currents, the bragg waves pass through these currents and change their amplitudes
- **atmospheric conditions**
 - local changes in wind speed/direction change bragg wave amplitudes

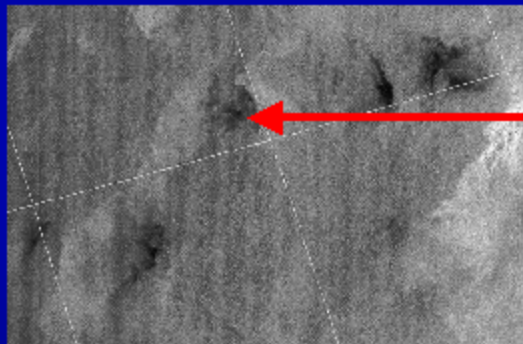
Synthetic Aperture Radar (SAR) contains information about a range of environmental conditions available day or night and in storms



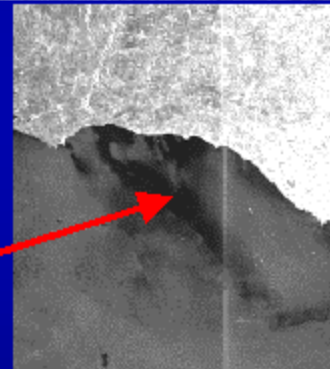
**Current
fronts**



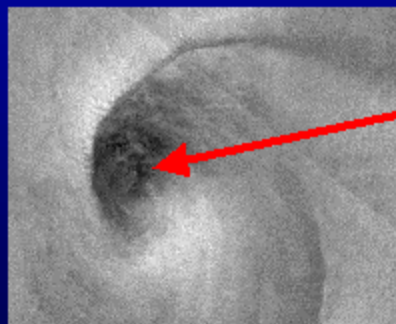
**Surface
wind field**



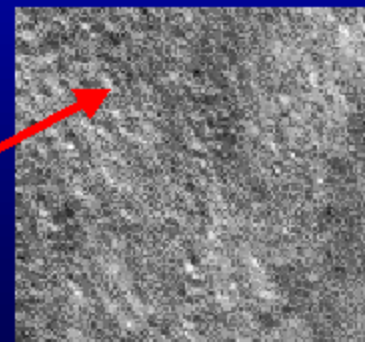
**Rain
cells**



**Oil
spills**



**Severe
storms**

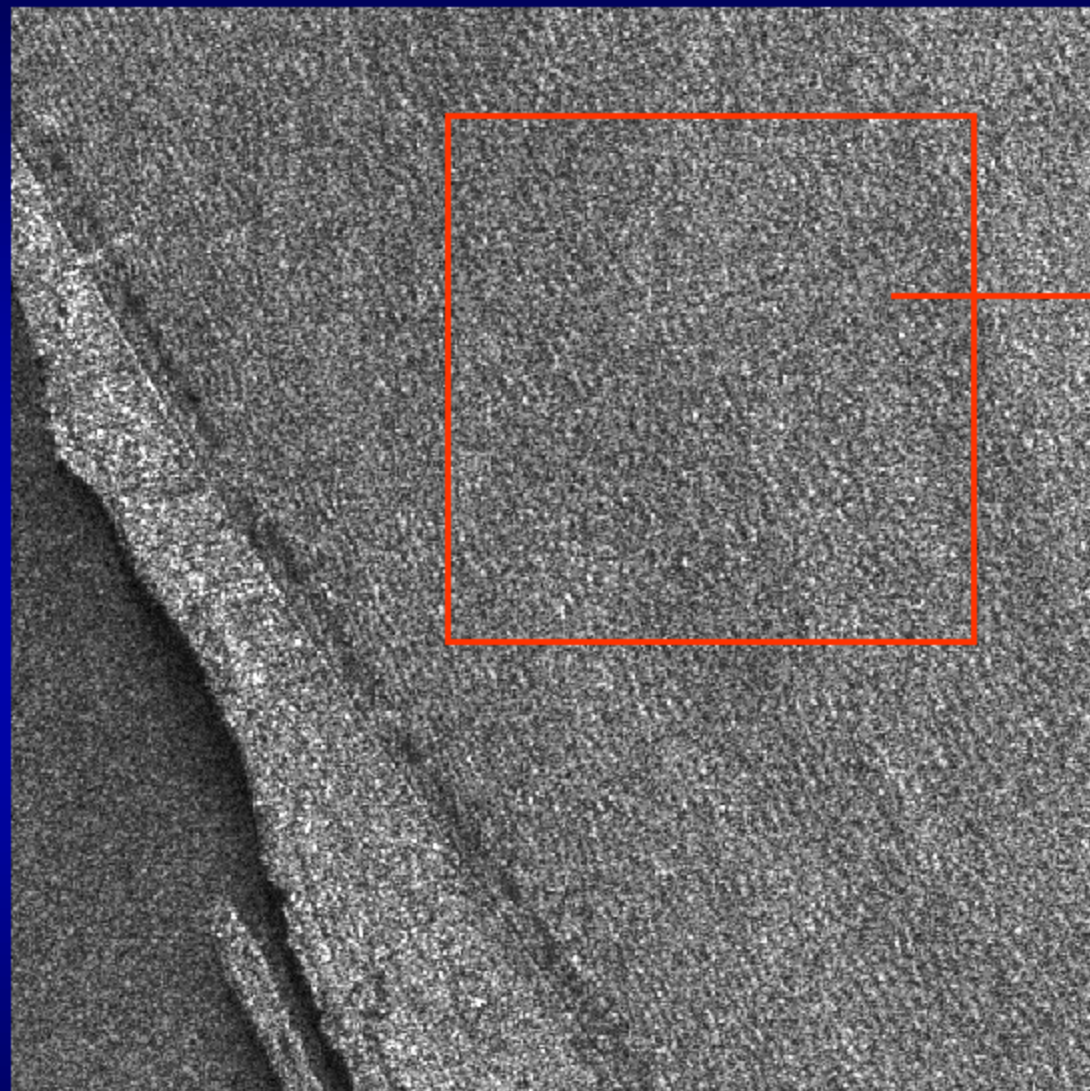


**Atmosphere
convective cells**

SAR Land Imaging

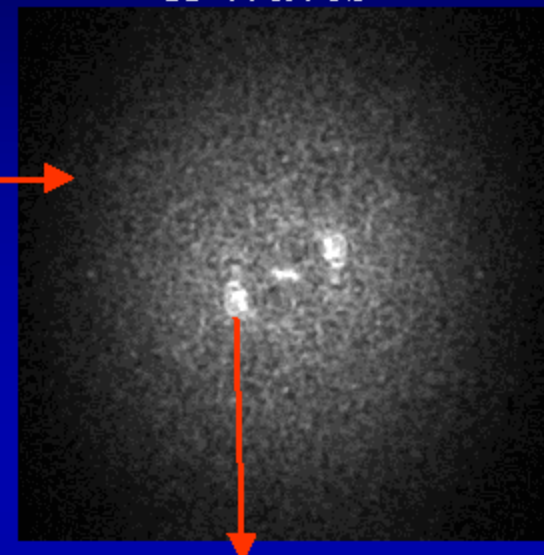
- **Radar cross section is dominated by: (1) surface roughness; (2) moisture content**
 - **rougher surface => brighter image**
 - **more moisture => brighter image**
- **Penetration and volume scattering is important**
 - **essentially no penetration occurs for water**
 - **if material contains bubbles, cracks, interfaces, then volume scattering causes a brighter image**
- **Since a SAR measures range, any topography causes shifts in range**
 - **tall structures get “laid over” toward the near-range**
 - **shadowing can occur, blocking the response from some targets**

Estimating Coastal Wave Conditions



ERS2 Radar Image 20 Nov. 1996

**Fourier Transform
of Waves**



**SAR Spectral
Inversion Algorithm**

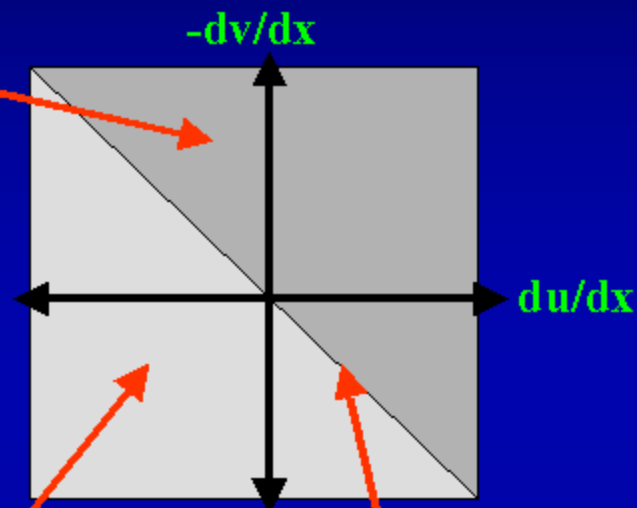
**Dominant Wave Length
Dominant Wave Direction
Dominant Wave Height**

Estimating Shear/Convergence Ratio Along Current Front



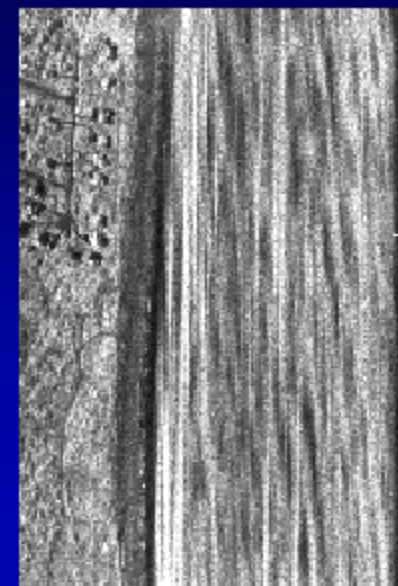
Region
of dark
signature

Region of bright signature



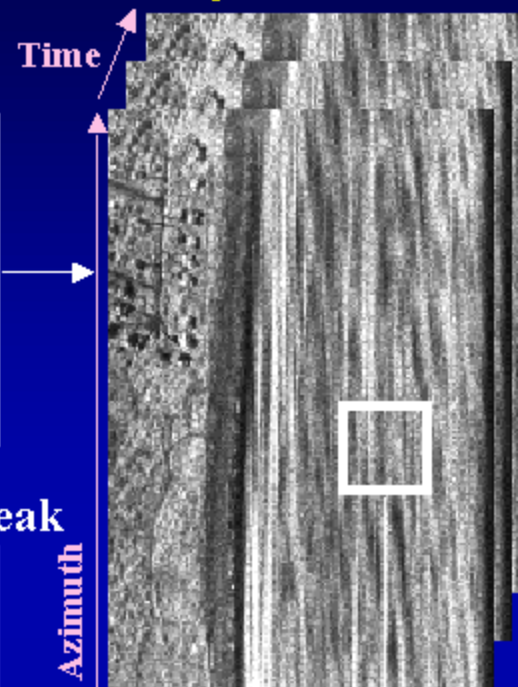
Angle of front with
respect to SAR look
direction

SAR Bathymetry Algorithm Summary

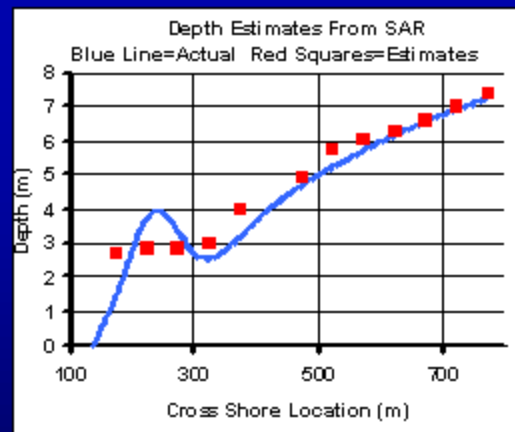


Start with complex image (or phase history).

Divide azimuth bandpass (or collection time) into time series of low-resolution images.



Estimate depth from Fourier peak



Use sinc interpolation to find the location of the peak energy in the 3-D Fourier transform.

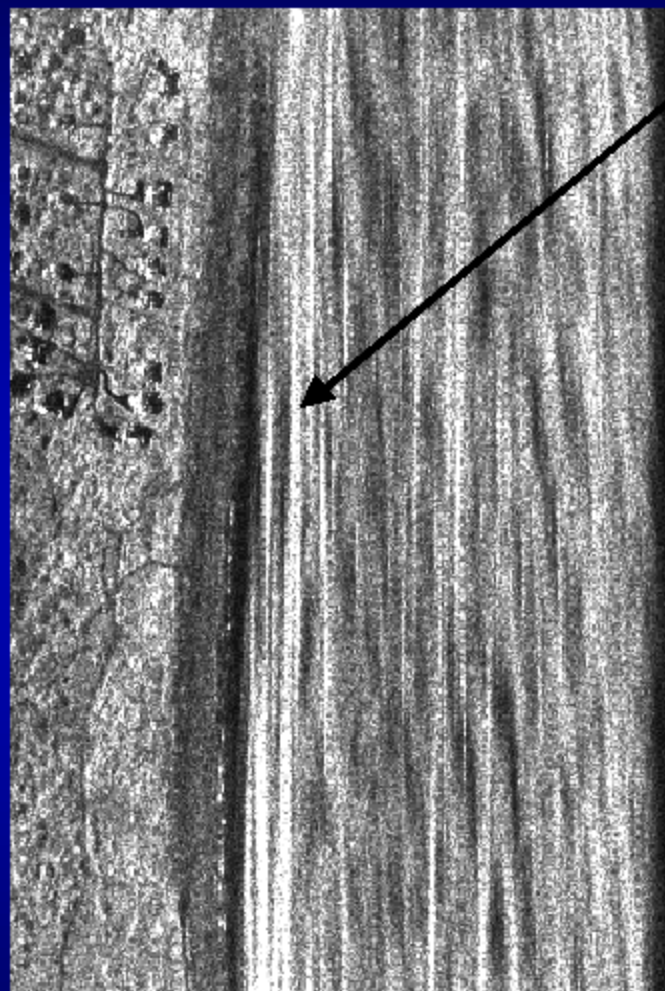
Shift peak location based on SAR imaging effects.

Translate shifted peak location into depth estimate.

Generate output products.

Do 3-D Fourier transform on spatial subsets of shoaling waves.

Breaking Wave Height From Smears



Use smear widths in surf zone to estimate range of radial velocities in breaking region

$$w_s = \frac{R}{V} \sqrt{\Delta V^2 G^2 + \sigma_v^2}$$

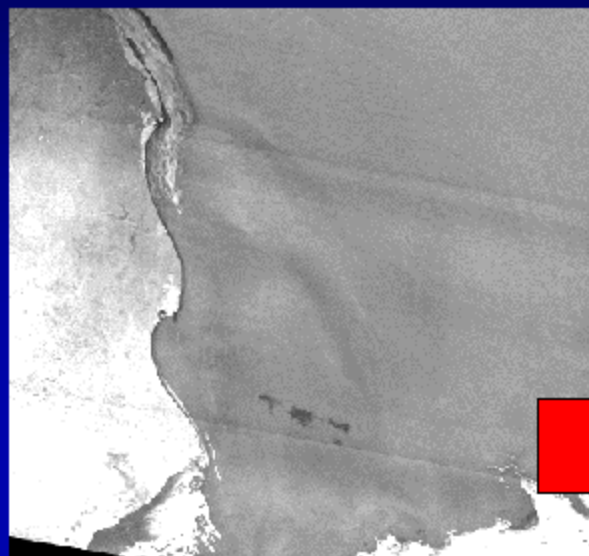
Estimate breaking wave height via ΔV and σ_v terms

$$\Delta V \approx 2.2 \sqrt{H_b}, \quad \sigma_v \approx 0.8 \sqrt{H_b} \quad \text{steady breaker}$$

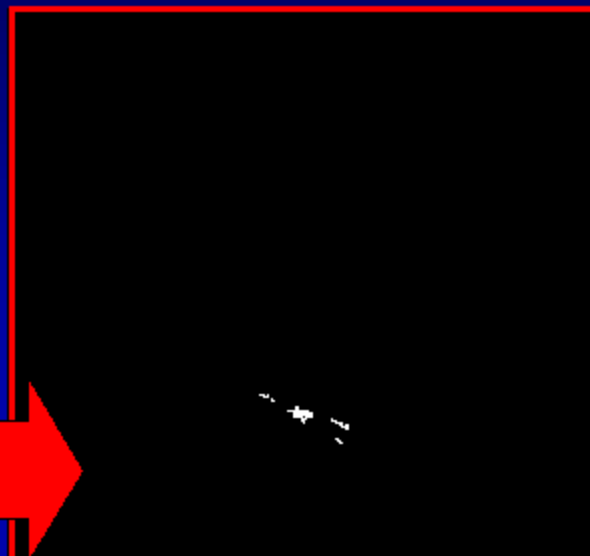
$$\Delta V \approx 0.8 \sqrt{H_b} \quad \text{entraining plume}$$

X-VV Airborne SAR Image of Duck, NC.

Automated Detection of Oilspills in SAR



Radarsat Image

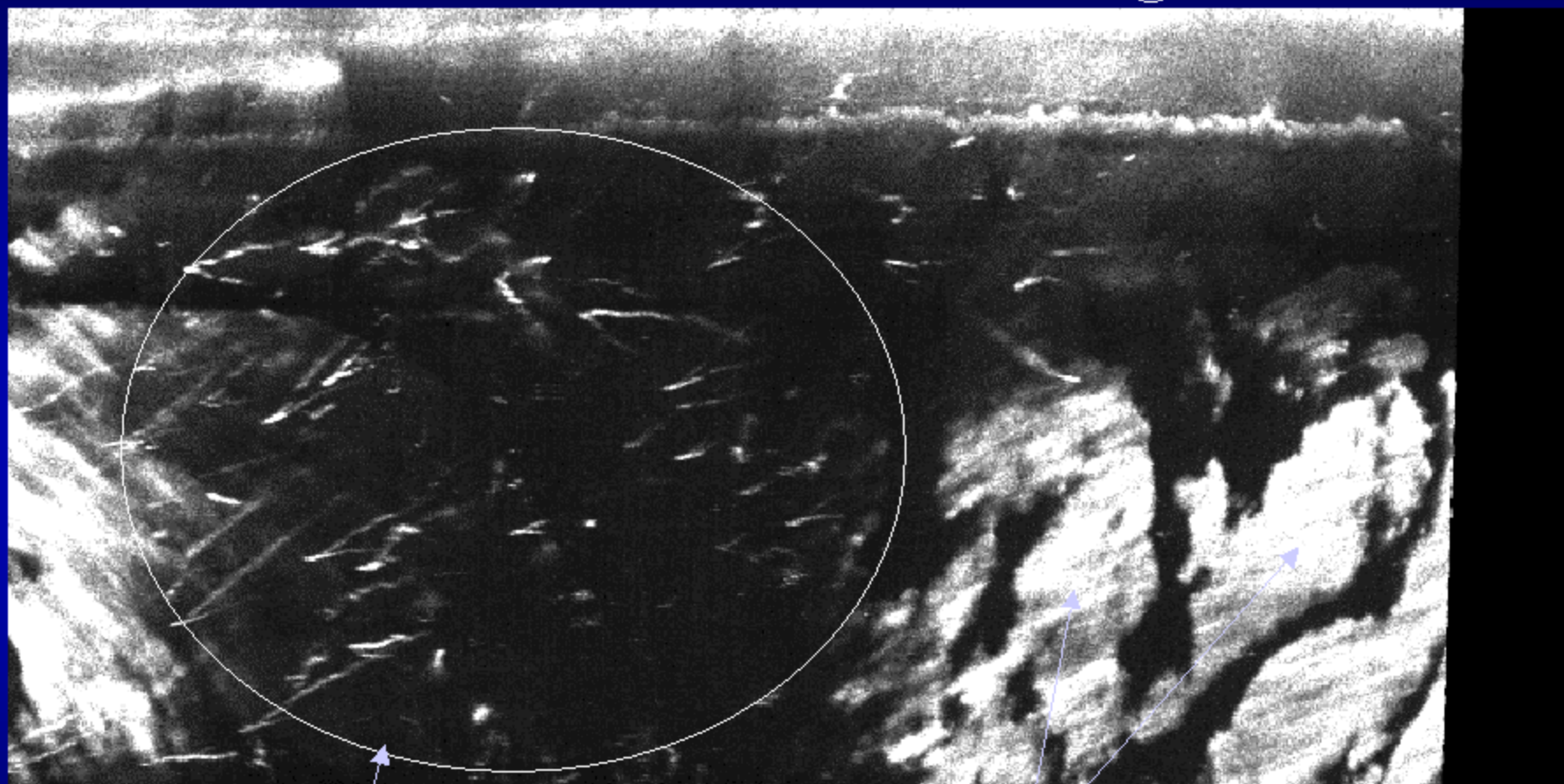


OilSpill Map

Characterize dark “blobs” in the image to determine those that are consistent with oilspill characteristics

Example of Whale Migration in SAR Imagery

L-VV Airborne SAR image



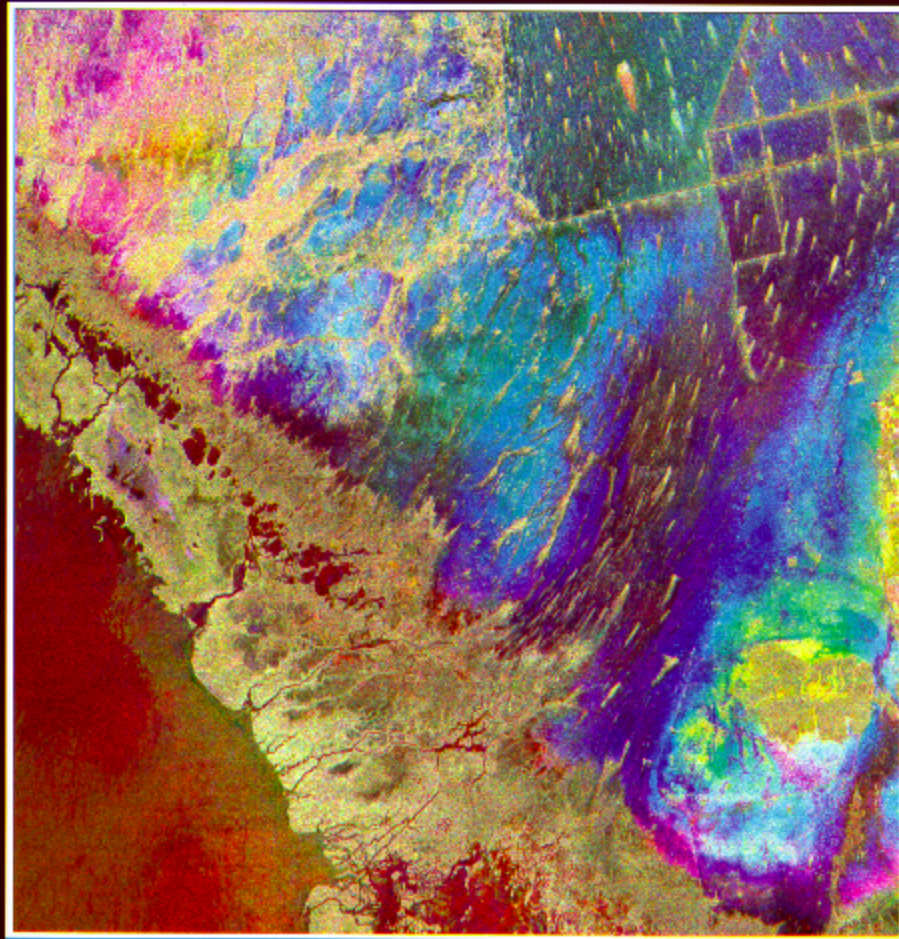
**Region of
whale signatures**

Wind roughened water

Coastal Hydrology From Multi-Temporal SAR Imagery

Three Date Composite ERS-1 Image

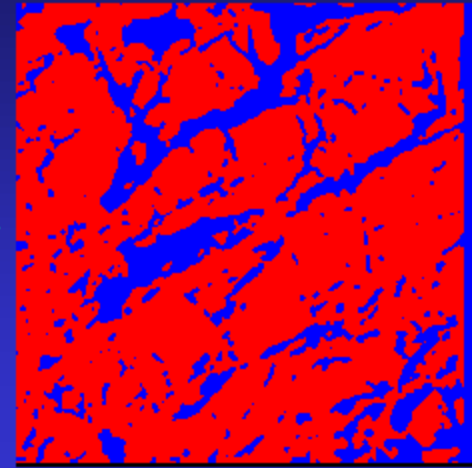
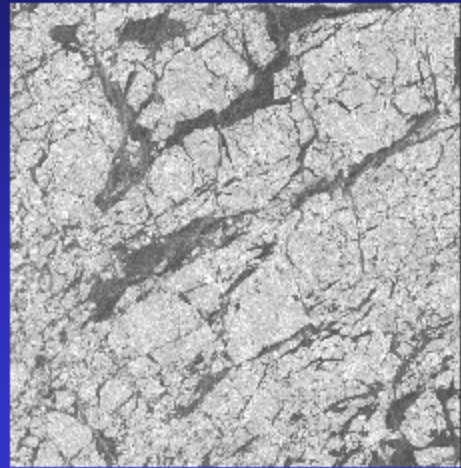
*Color
determines
flooding state
over all
seasons*



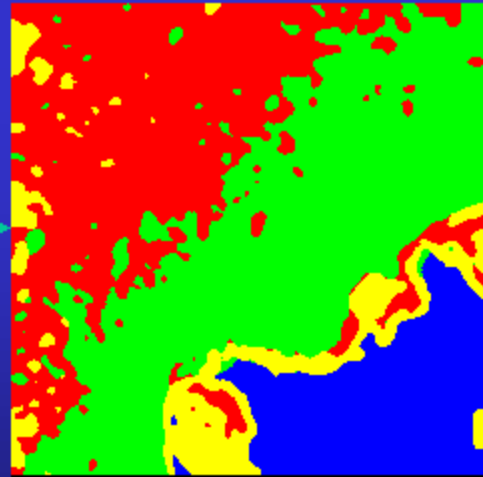
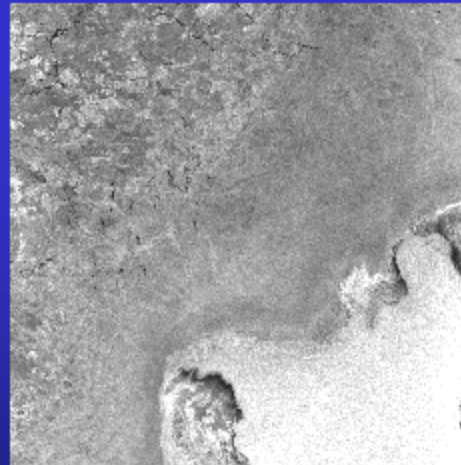
- November 06, 1995 ERS-1 Image - Late Wet Season
- June 19, 1995 ERS-1 Image - Early Wet Season
- May 15, 1996 ERS-1 Image - Late Dry Season

Sea Ice Classification Algorithms

**Look-Up Table
(Pack Ice)**



**Supervised
Classification
(MIZ)**



**Ice Characterization
(thickness, roughness, etc)**

Automated Supervised Classification

